Impact of Jet Fuel Characteristics on Airplane Operations

RROI # 24-183310-BCA

In-Flight Boost Pumps Low Pressure Indication

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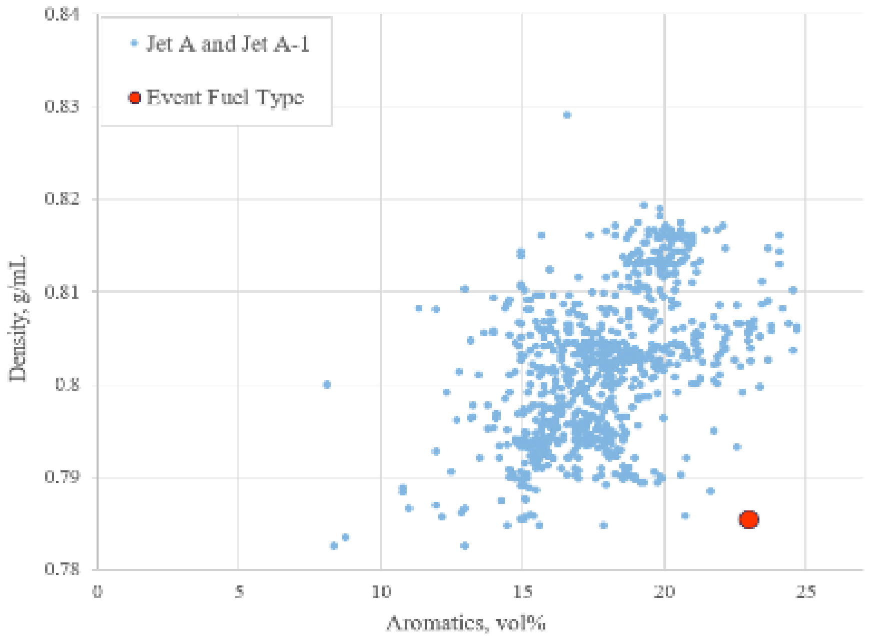
Boost Pumps Low Pressure Indication: Overview

Fuel Property Analysis

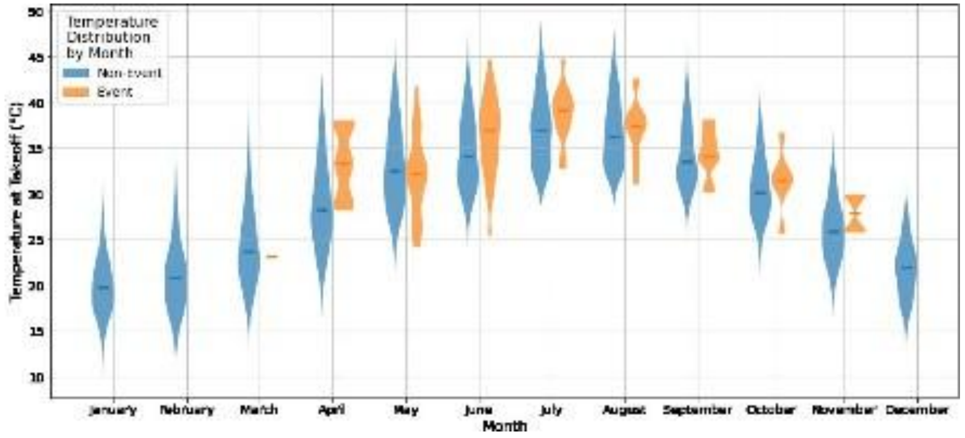


Issue/Background

- Approximately 11.5 hours into flight, a 777 experienced a temporary engine rollback after both fuel pumps on the left main tank lost the ability to provide pressure feed
- Approximately 11 hours into the flight, a 787 experienced a loss of pressurized fuel feed to the left engine. Almost 1 hour later, the aircraft experienced a loss of pressurized fuel feed to the right engine

Initial Investigation

- An increasing trend of fuel pump low pressure indication events that was not affecting other operators
- Events occurring:
  - Primarily outbound from the same airport
  - Greater than 12 hours flight time
  - Primarily during the period from April to October each year
- All post-flight inspections revealing no findings for fuel system components



Flight Data Analysis – Takeoff Temperatures

Density vs. Aromatic Content

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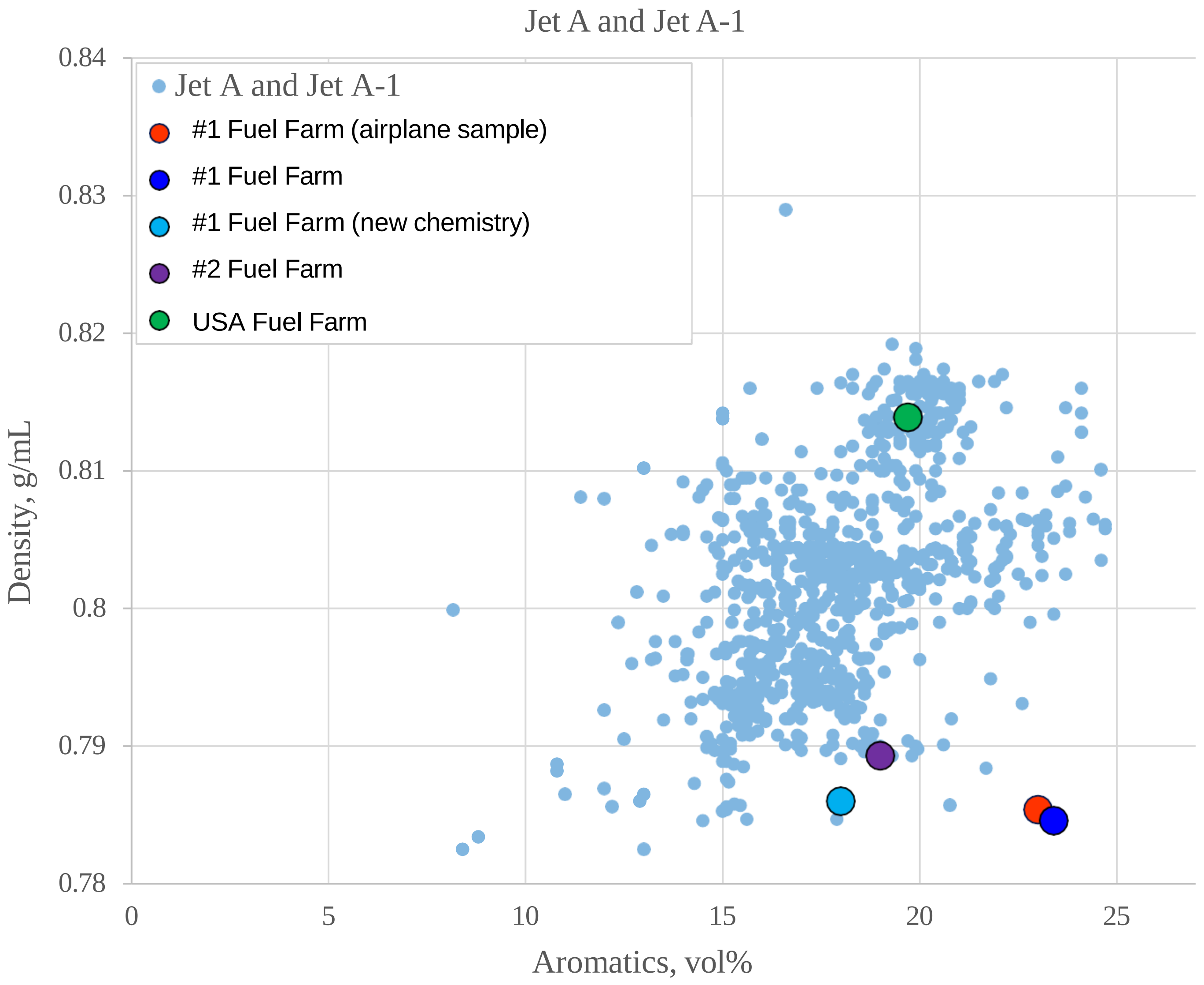
Fuel sourced from an International Airport Fuel Farm has an unusual combination of low density and high aromatic content.

Results from relevant samples were compared to data extracted from the PQIS database.

PQIS: Petroleum Quality Information System

Contains fuel properties data for Jet A, Jet A-1, JP-8, JP-5, etc.

Over 8000 fuel entries



Compiled Data of Analyzed Fuels

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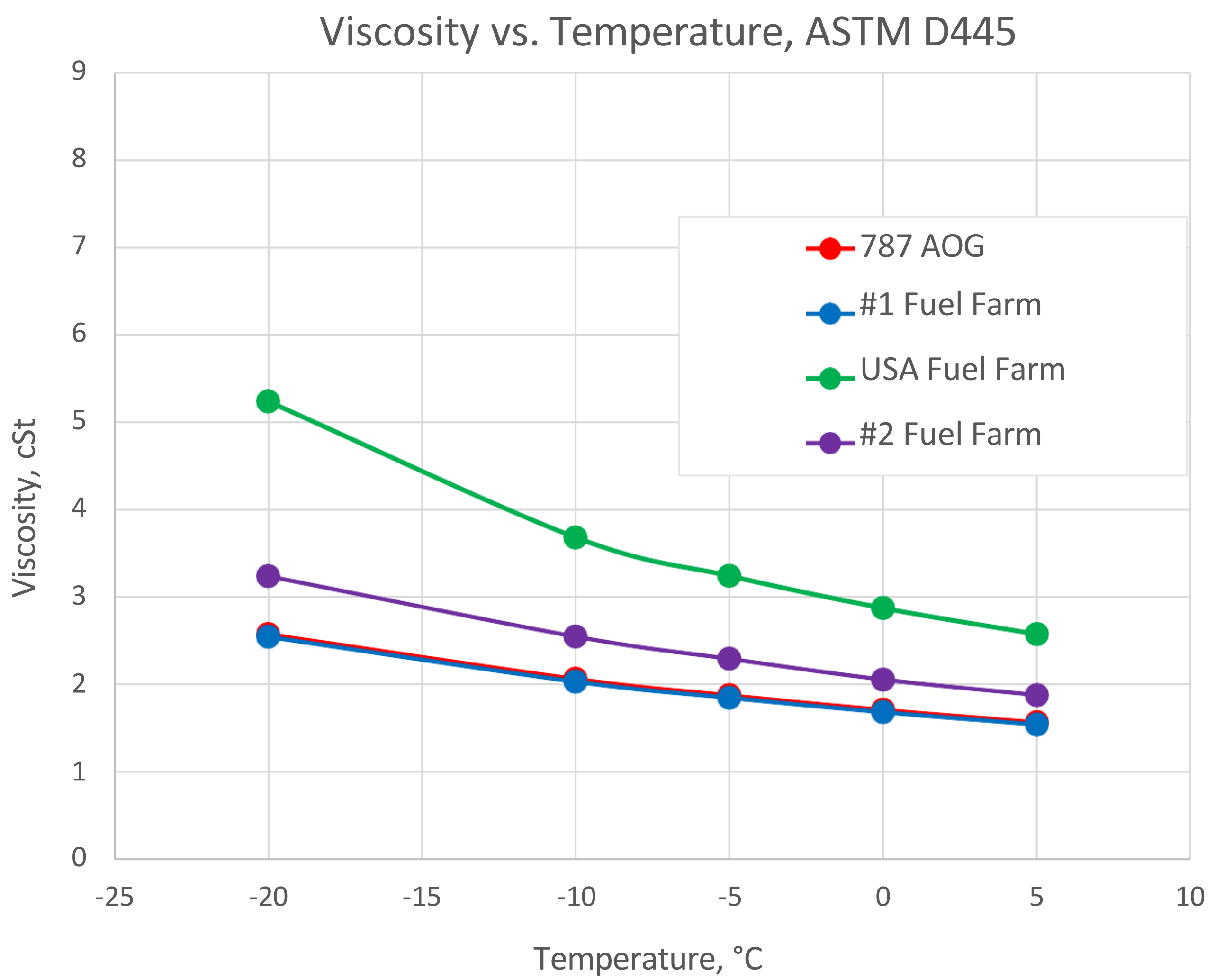
Property	Test Method	Airplane Sample from #1 Fuel Farm	#1 Fuel Farm	#2 Fuel Farm	USA Fuel Farm
Aromatic Content, vol %	ASTM D1319	23.0	23.4	19.0	19.7
Density @ 15°C, g/mL	ASTM D4052	0.7854	0.7846	0.7893	0.8139
Viscosity, cSt	ASTM D445				
-20°C		2.573	2.542	3.236	5.233
-10°C		2.062	2.030	2.546	3.679
-5°C		1.875	1.846	2.292	3.240
0°C		1.709	1.682	2.055	2.872
5°C		1.566	1.540	1.878	2.573
Freezing point, °C	ASTM D5972	Low wax @ -66	Low wax @ -66	<-57.7	-46.9
Saturated with water at 40°C		Low wax @ -67	Low wax @ -67	-58.1	-49.6
Cloud point, °C	ASTM D5773	No wax at -66.5	-66.5	<-61.4	-52.5
Saturated with water at 40°C		-66.0	-58.3	-58.3	-54.9
Pour Point, °C	ASTM D5949	<-67.0	<-67.0	<-66.0	-55.0
Saturated with water at 40°C		<-67.2	<-67.0	<-67.0	-65.0
Vapor Pressure, PSI	ASTM D6378				
20°C		0.05	0.06	0.04	0.02
30°C		0.11	0.10	0.08	0.05
40°C		0.16	0.16	0.13	0.10
50°C		0.27	0.26	0.22	0.17
60°C		0.42	0.41	0.36	0.27
Composition, wt %	GCxGC				
n-paraffins		26.62	27.02	22.81	17.60
*iso*paraffins		29.75	29.68	33.97	26.37
cycloparaffins		18.94	17.94	22.56	36.58
aromatics (alkyl benzenes + cycloaromatics)		23.90	24.70	19.77	17.40
naphthalenes		0.80	0.66	0.89	2.05
Water Solubility, ppm	KF				
40°C		193.8	187.2	158.1	153.9
-10°C		39.8	31.3	30.7	46.6
delta 40°C/-10°C		154.0	155.9	127.4	107.3

Viscosity

The viscosity of the fuel is unusually low of 2.542 cSt at -20°C compared to a control fuel (USA) of 5.233 cSt at -20°C.

Fuel	Extrapolated viscosity, cSt	
	20°C	40°C
#1 Fuel Farm	1.2	0.9
USA Fuel Farm	2.0	1.4



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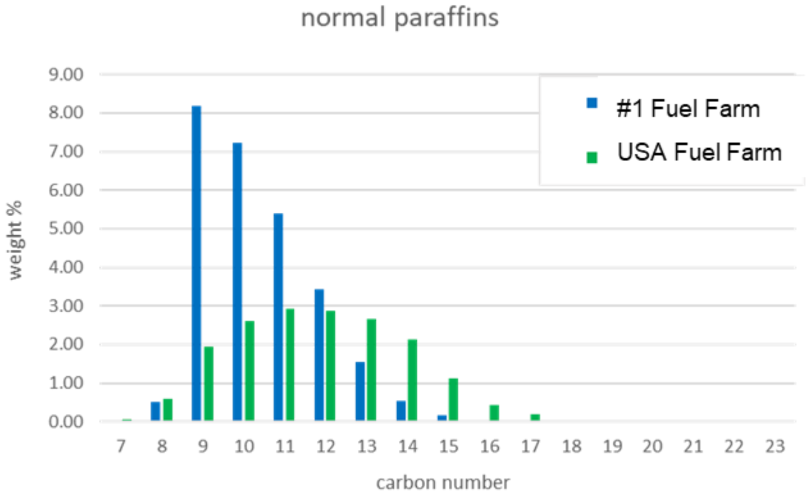
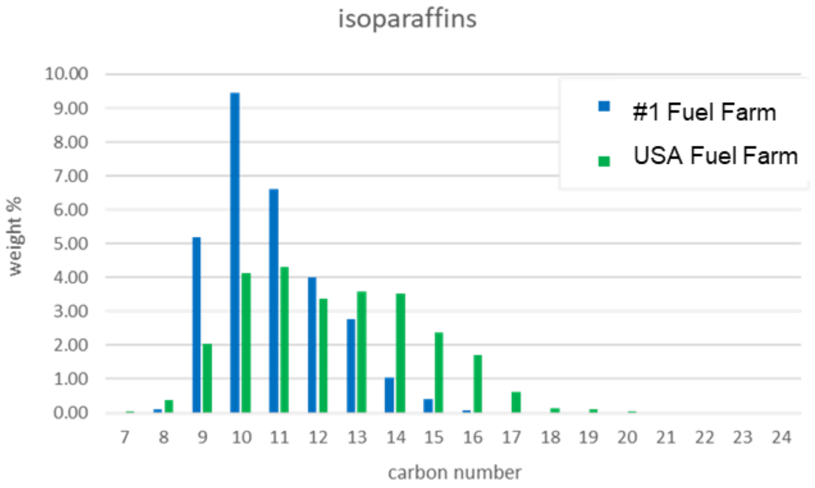
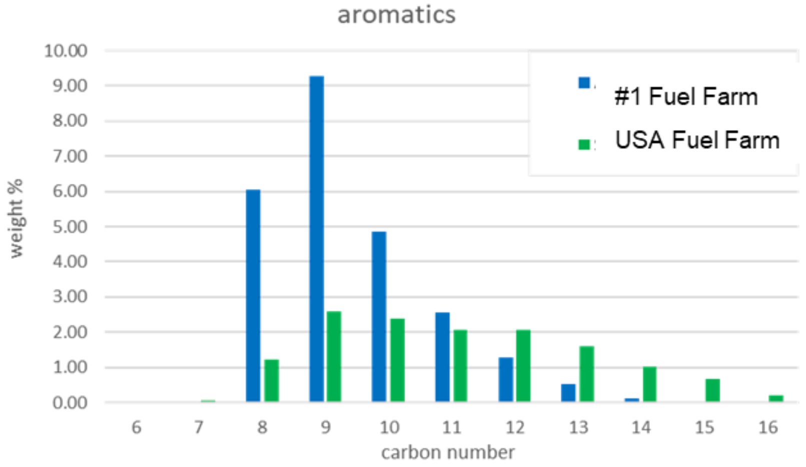
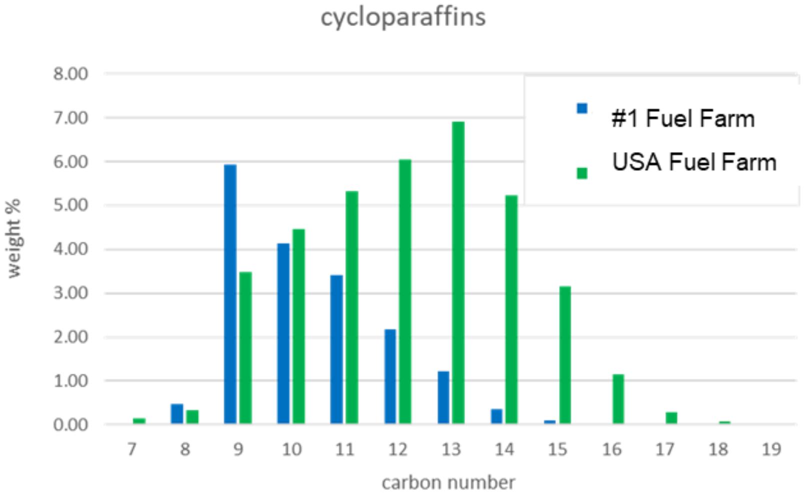
Hydrocarbon Distribution

- The #1 Fuel Farm fuel does not have a typical, “bell shaped” distribution of the major hydrocarbon classes.
- **USA Fuel Farm** fuel has a typical distribution of all analyzed classed of molecules (normal, iso, cycloparaffins and aromatics).
- The **#1 Fuel Farm fuel** has a high concentration of aromatic compounds, and they are predominantly of the lower molecular weight (C8 – C10).
- Such fuel composition is the likely contributing factor to the observed water solubility characteristics.
  - Aromatic molecules with lower molecular weight (higher aromatic character) have higher water solubility than aromatic compounds with higher molecular weight (higher paraffinic character).









Investigation – Aircraft, Component, Rig Test

Aircraft investigation resulted in no failures found in mechanical or electrical components:

- Pump mechanical features were in working order
- Pressure switches were functional
- No presence of standing water found in sump samples

Prioritized root cause investigation:

- Configuration review and event aircraft inspection
- Fleet history/data analysis
- Fuel properties, water content, and contamination
- Boost pump/pressure switch components
- Environmental effects combined with departure airport fuel

Testing included the following:

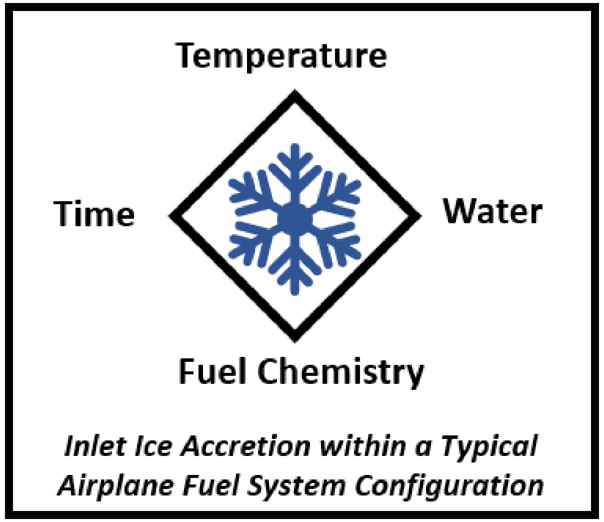
- Fuel property testing
- Boost pump component testing
- Inlet screen testing
- Lab scale fuel system rig testing

Boost Pump

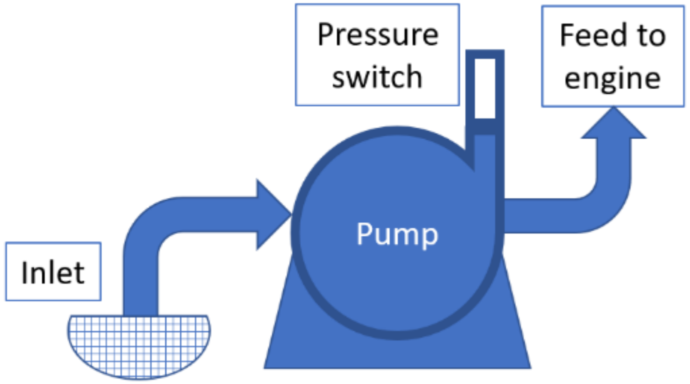
Lab Scale System Rig Test

Root Cause Investigation

- Analyzed fuel samples suggested the possibility to hold a higher concentration of water
  - High aromatic content, low viscosity, low density, and surfactants (all fuel properties within Jet A-1 limits)
- Specific fuel composition combined with operating conditions led to significant ice accretion on pump inlet screens
- Requested fuel supplier to change the fuel properties to reduce ability of the fuel to hold water.
- The fuel provider changed the fuel properties in February 2023 with no further events recorded to date from the original airport.
- Voluntary data collection from operators
- Continuous monitoring of AHM fleet data



Pump Inlet Ice Accretion Simulated on Fuel System Test Rig



Pump Inlet Screen (Rig Test)

Ice Accretion On Pump Inlet Screen (Rig Test)

Inlet screens use No. 4 mesh, commonly used throughout the aviation industry

Contamination Analysis - Background

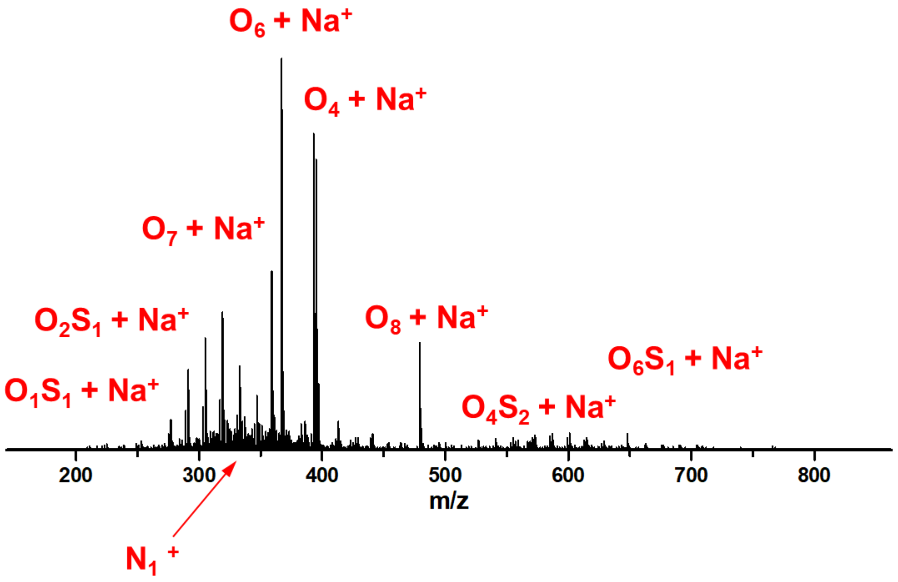
Contamination was suspected which can aid with increased water solubility (e.g. surfactants) as well as high molecular weight material.

Fuel samples were sent to the Florida State University (FSU) High Magnetic Field Laboratory for analysis using their patented method for polar species separation with a hydrated silica technique.

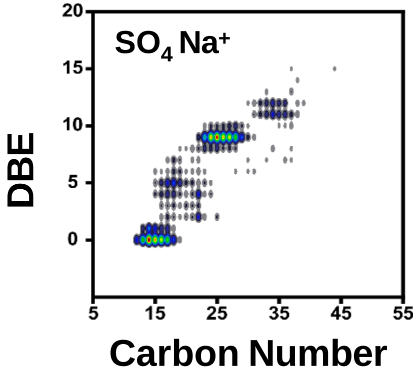
Kaiser, N. K.; Quinn, J. P.; Blakney, G. T.; Hendrickson, C. L.; Marshall, A. G. A Novel 9.4 T FTICR Mass Spectrometer with Improved Sensitivity, Mass Resolution, and Mass Range. J. Am. Soc. Mass Spectrom. 2011, 22, 1343−1351.

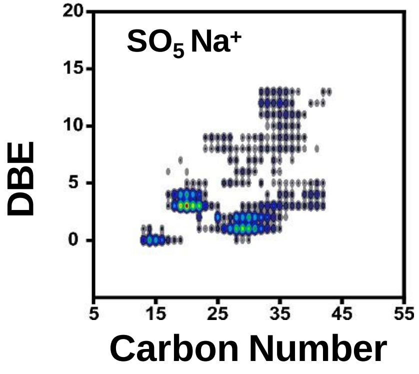
Jacqueline M. Jarvis, Winston K. Robbins, Yuri E. Corilo, and Ryan P. Rodgers Novel Method To Isolate Interfacial Material, *Energy Fuels* 2015, 29, 11, 7058–7064

Detected typical fuel heteroatomic species: substituted pyridines, alkyl amines, oxygenates, e.g. naphthenic acids, etc. Sulfoxides (S_xO_y) and sodiated sulfoxides were also detected, which are not typically observed in finished jet fuel.



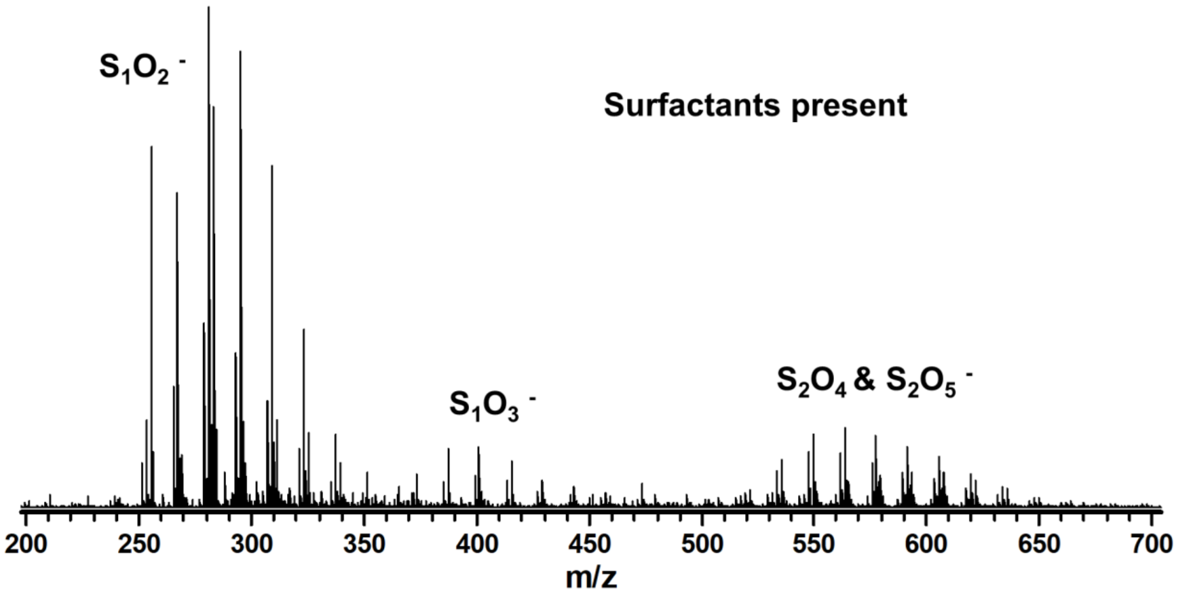
Icing Rig Sample 4
(+) ESI



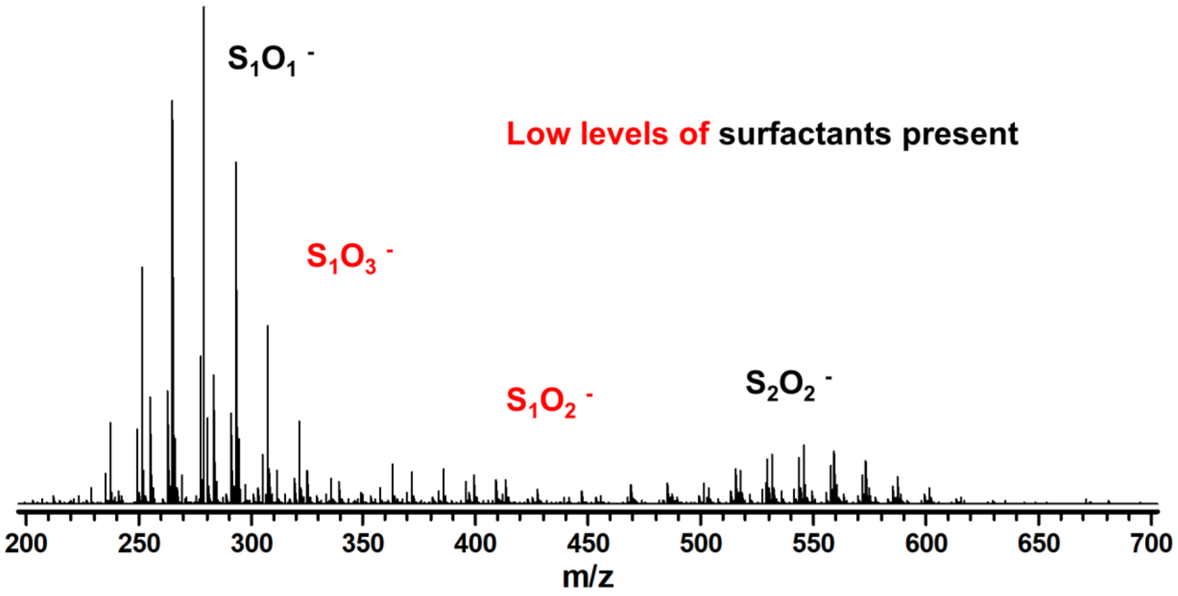


Problematic Fuel Before and After Clay Treatment for Rig Testing

Problematic fuel sample as received



Problematic fuel sample after clay treatment*



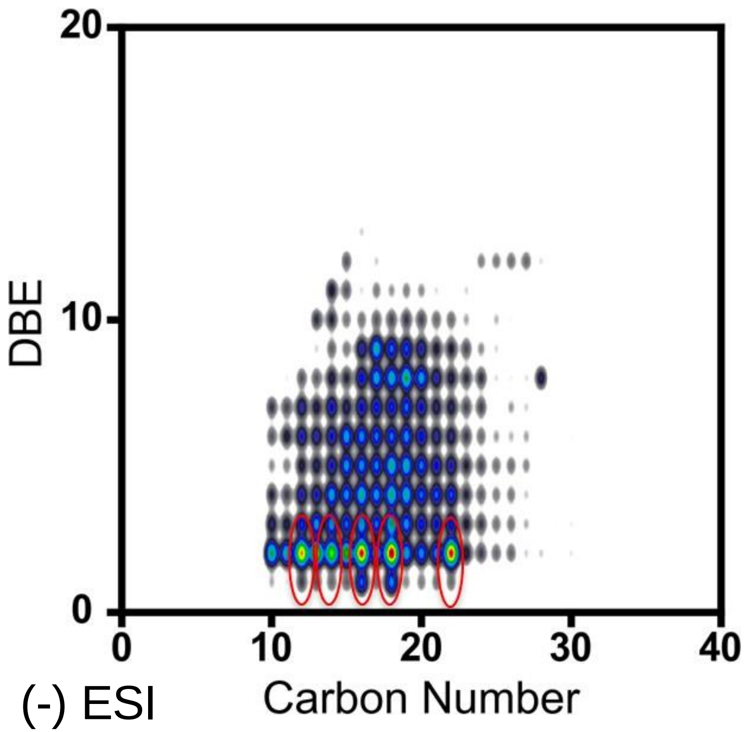
*Icing rig scale after the second round of clay treatment

Clay treated fuel:

- ~10X lower signal-to-noise of SO_x species compared to untreated problematic fuel sample
  - Although the clay treatment was not completely effective in eliminating all contaminants, it did demonstrate a commendable level of efficacy in removing a significant portion of the polar impurities.
- S_1O_1 and S_2O_2 species still present after clay treatment. These species are most likely not sulfoxides but are reaction products containing an alcohol or similar functionality separate from sulfur.

Naturally Occurring and Synthetic Sulfoxides Observed in Problematic Fuel

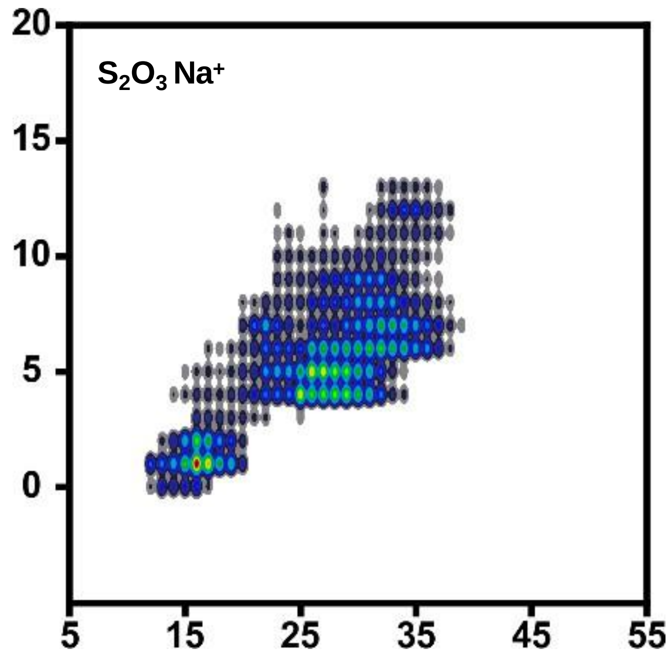
Airplane Sample from #1 Fuel Farm



(-) ESI

Even carbon number preference suggests that these species are most likely synthetic in origin.

Problematic Fuel Icing Rig Sample

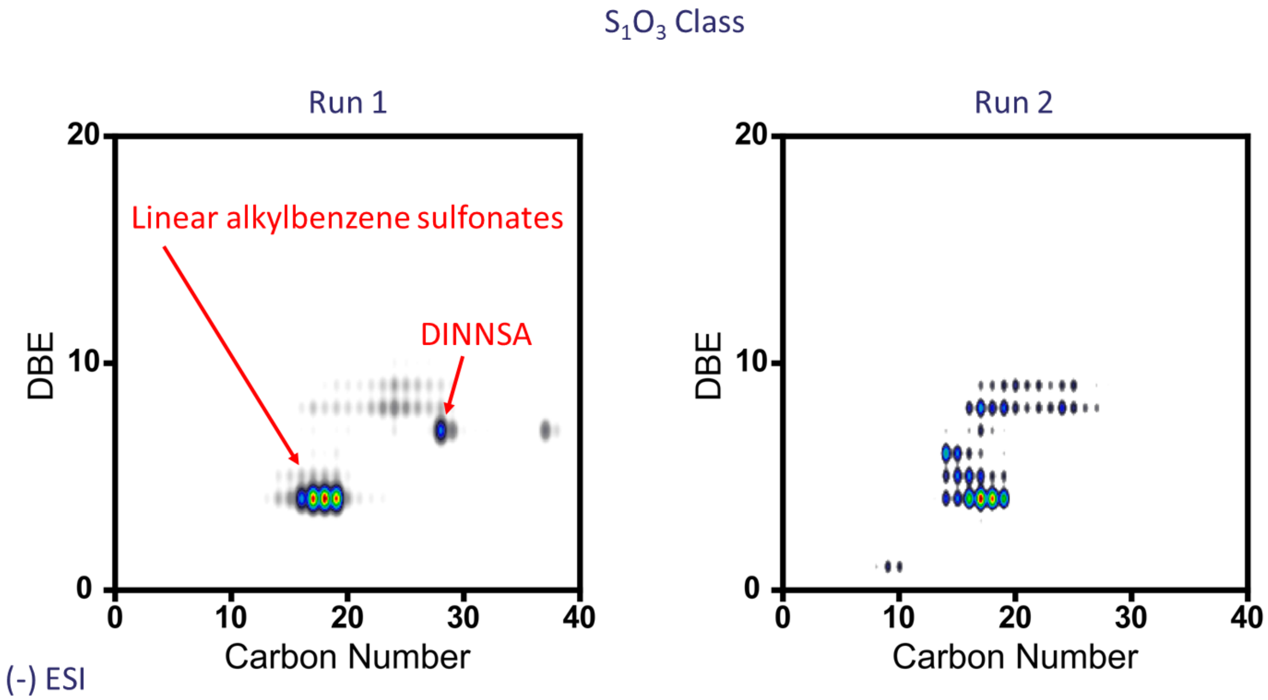


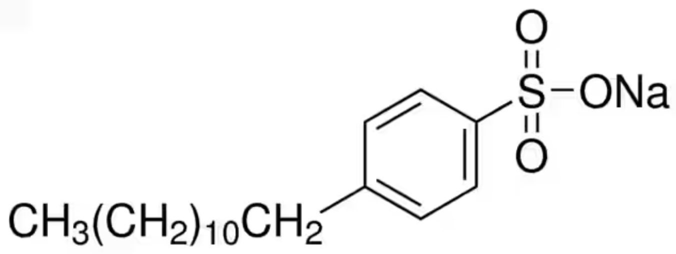
(+) ESI

Diversity of species suggest naturally occurring sulfoxides.

Contamination Analysis – Negative Mode S_1O_3 Class

Airplane Sample from #1 Fuel Farm

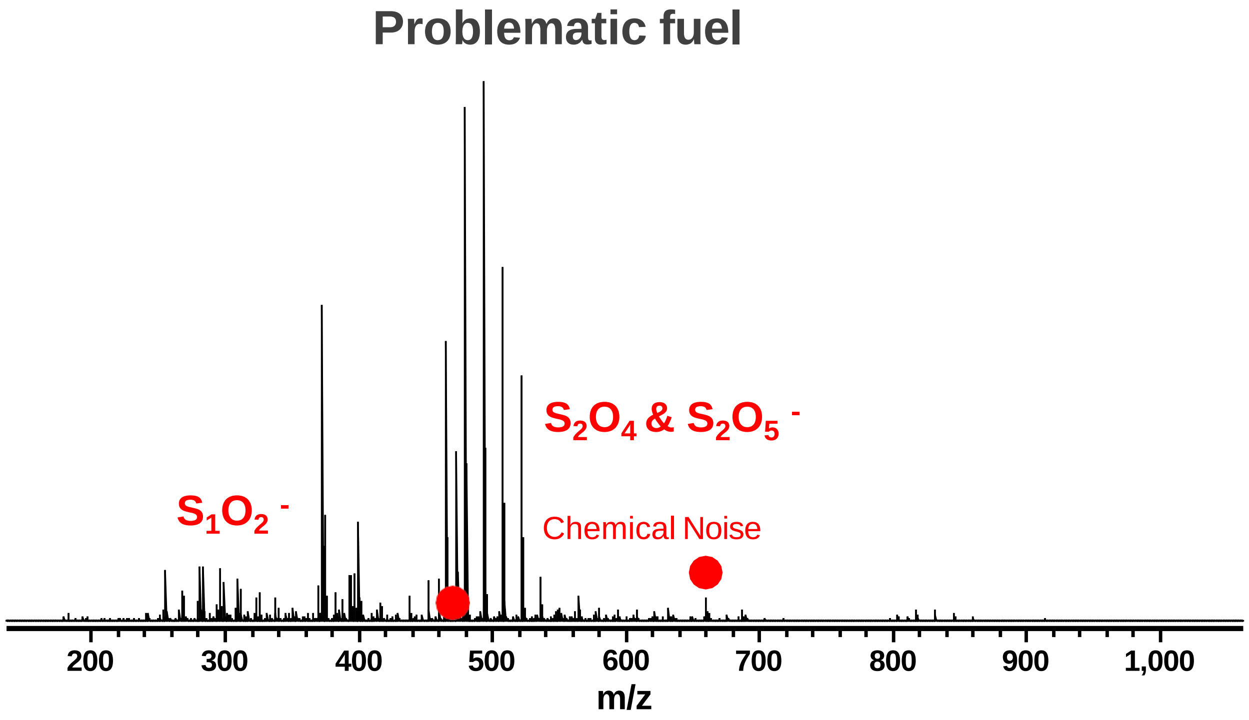


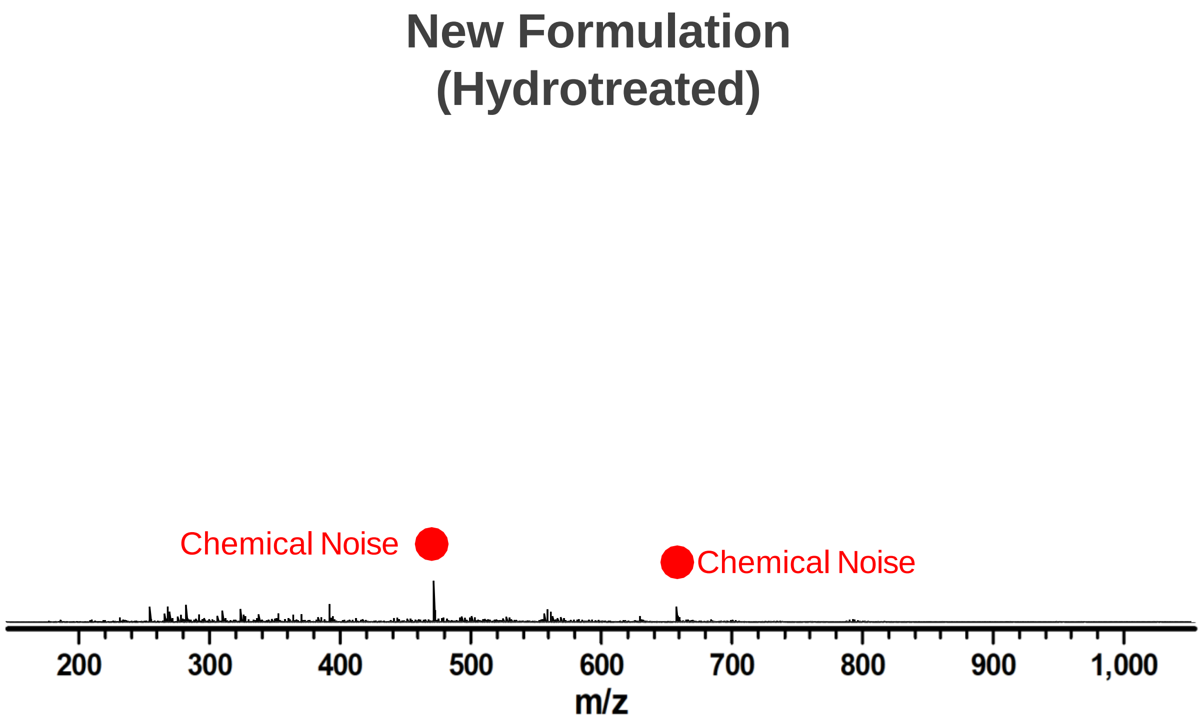


Example LAS: sodium dodecylbenzenesulfonate

- DINNSA is from static dissipator additive (SDA).
- Linear alkylbenzene sulfonates (LAS's) are a contaminant which is not present in SDA.
  - LAS's are used everywhere in oil – drilling, refineries, etc. They are seen in fuels, crude oils, deposits.
- If LAS was present in fuel that has been exposed to water, the original concentration present in the fuel could be much higher than what was detected since the LAS's preferentially migrate to the fuel-water interface and partition into the water.

Comparison of Original Problematic Fuel and New Formulation (Negative ESI)

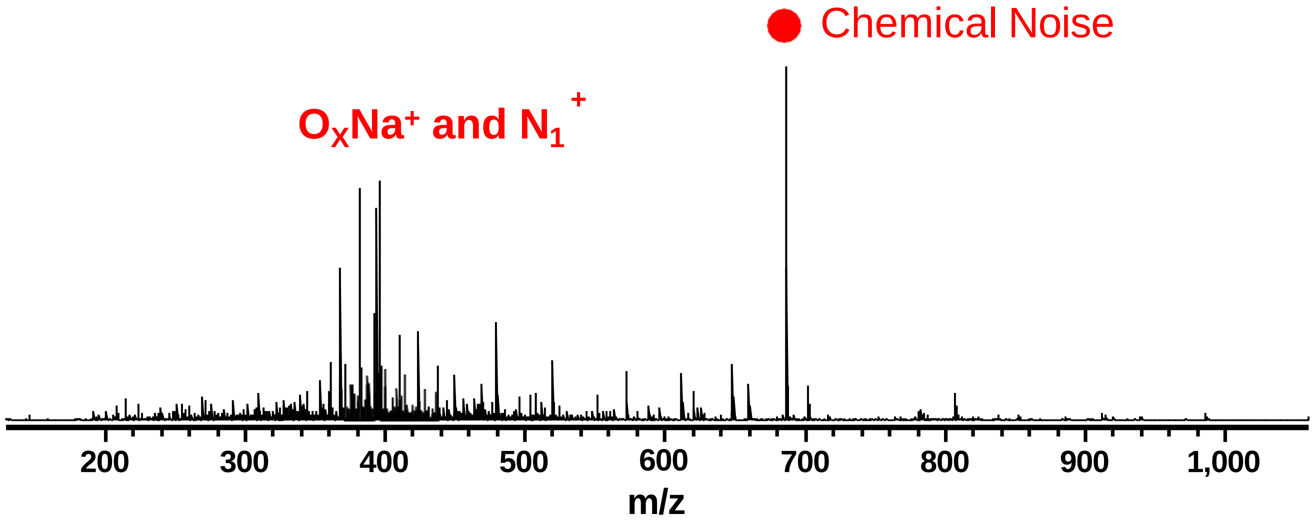


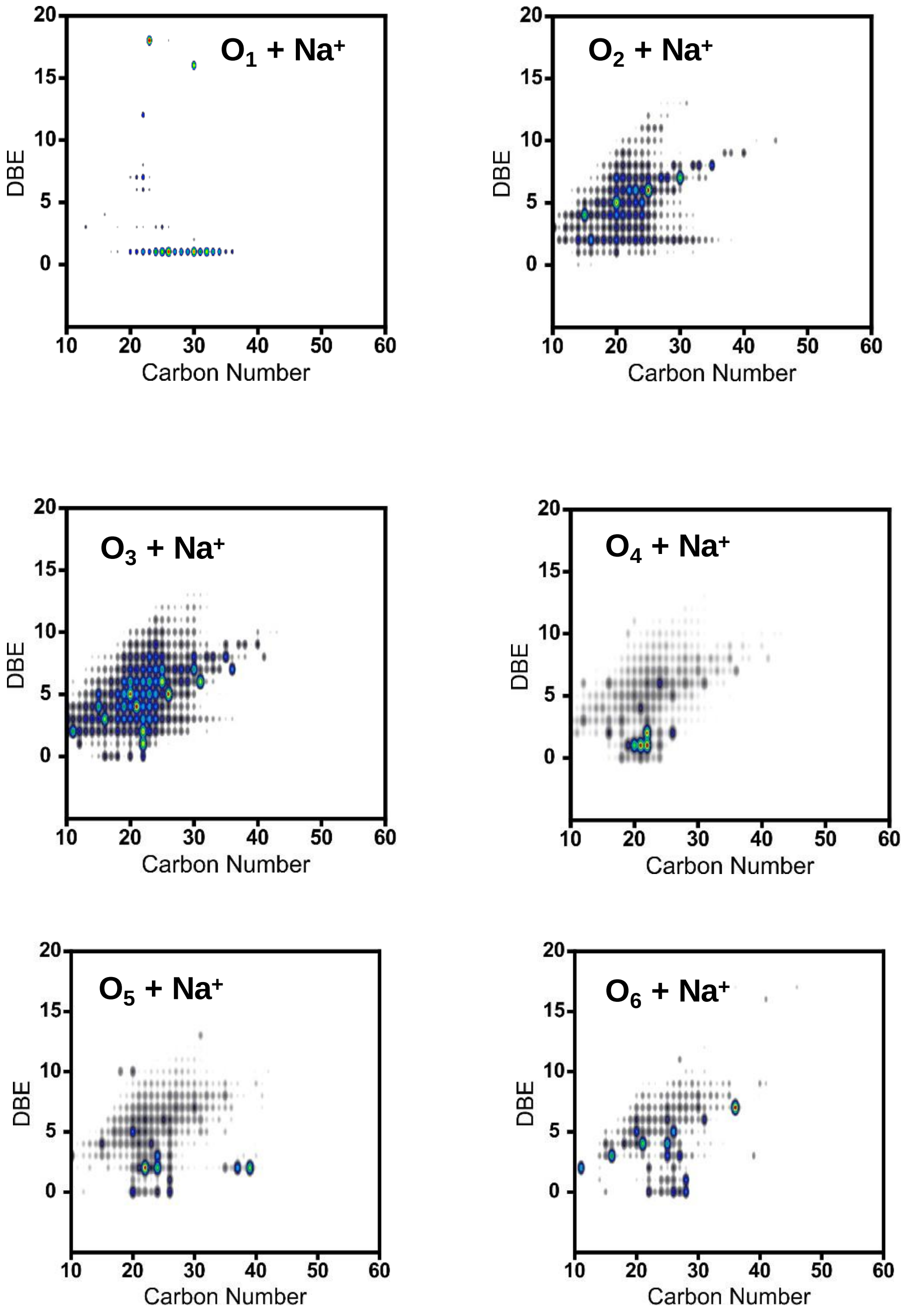


There are far fewer polar species in new formulation compared to the fuel from the previous process.

New Formulation of Fuel (Positive ESI)

Small amounts of sulfoxides, but no sodiated SO_X detected





Some sodiated oxygenates were observed in the new formulation, but no sodiated S_xO_y was detected.

Contamination Analysis - Summary

- **Sulfoxides are not expected to survive the refining process. A possible way to get the sulfoxides into the final fuel is to blend in a material that has never seen the refinery.**

- **Linear alkylbenzene sulfonates (LAS) were observed. It is likely that the concentration of LAS in fuel was originally higher due to LAS preferential partitioning to the water phase.**

- **C16, C18 and C20 organic phosphates were never observed in petroleum samples analyzed by FSU.**

- **Clay treatment removed significant amount of surfactant S_xO_y species**
    - SO and S_2O_2 species remaining after clay treatment are likely no sulfoxides
    - No low boost pump pressure observed after 2nd round of clay treatment.

- **Changes in refining process resulted in new fuel formulation which does has very little polar species and no sulfoxides.**
    - No in-service issues observed since new formulation has been in use.

Rig Testing Summary

- **Low boost pump pressure observed with problematic fuel using a realistic amount of added water.**
- **No low boost pump pressure observed with USA fuel using same amount of added water as problematic fuel.**
  - Water added to cause low boost pump pressure was significantly higher and unrealistic.
- **No low boost pump pressure with added aromatics to USA fuel.**
- **No low boost pump pressure after clay treatment of problematic fuel.**
  - More than one round of clay treatment was required.
  - Extent of clay treatment required is currently unknown.
- **No low boost pump pressure with some surfactants – needs further evaluation.**
  - Unknown concentration of surfactants present in problematic fuel – concentration added in testing may have not been representative.

Next Steps for Industry Evaluation

Data Shows	Indication	Needs Further Evaluation	Conclusion	Comments
X			Surfactant in fuel allows for more water than previously considered in industry	Demonstrated by Karl Fischer data.
		X	Hydrocarbon distribution affects icing issue	Looking for industry collaboration to further investigate.
		X	Density affects icing issue	Looking for industry collaboration to further investigate.
	X		Aromatic % does not affect icing issue	May contribute when in combination with other factors such as surfactants.
		X	Viscosity affects icing issue	Looking for industry collaboration to further investigate.
X			Problematic fuel chemistry causes icing issue with lower amount of water compared to USA fuel	Demonstrated in rig testing.
X			Nominal USA fuel does not have an icing issue with a realistic amount of water in the system	Demonstrated in rig testing.
X			Chemical species responsible for issue can be removed by clay treatment fuel (surfactant is a polar species)	Extent of clay treatment required is unknown. However, more than one round of treatment was needed.
		X	Surfactant alone, regardless of fuel composition, causes icing issue	Unknown concentration of surfactants present in problematic fuel – concentration added in testing may have not been representative. Looking for industry collaboration to further investigate.

Need to deconvolute contribution of fuel bulk composition and surfactant contamination.

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